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Edward L. Ginzton Laboratory
Stanford University
Stanford, CA 94305

Annual Technical Report

to

The Air Force Office of Scientific Research

&

The Army Research Office

Research Studies on Extreme Ultraviolet and Soft X-Ray Lasers

Contract F49620-88-C-0120

For the Period
1 September 1989 - 31 August 1990

Principal Investigator
S. E. Harris

Section 1

Introduction

The ~~overall~~ purpose of this program is to study the physics, technology, and spectroscopy of extreme ultraviolet (XUV) and soft x-ray lasers. The objective of our work is to develop a class of fixed frequency and tunable lasers whose wavelengths span the 100 Å to 1000 Å spectral region. We are also interested in developing concepts and ideas that are applicable to other regions of the spectrum.

During the previous contract period we have emphasized work in several areas. These are: (1) The development of extreme ultraviolet sources of radiation based on pumping with synchronous traveling-wave x-rays. (2) The theoretical study and the beginning of experimental studies on lasers without inversion and on laser-induced transparency. We have also begun studies on new types of nonlinear optical processes using electromagnetically induced transparency.

This has been a particularly exciting contract period. Our femtosecond timescale laser system is finally together and has an output energy of $\sim$ 75 mJ 100 fs. We have recently made a H_2 laser operating at 116 nm that is pumped by x-ray produced electrons. The laser has a gain of about exp(30) and runs stably and easily.

As I write this we have just demonstrated for the first time a phenomena which we have termed as laser induced transparency. Early results indicate that we are able to change a transmittance of exp(-15) to exp(-1).

Before proceeding we note that the work described here has been, and will continue to be, jointly supported by other agencies, primarily the U.S. Office of Naval Research and the U.S. Strategic Defense Initiative Organization.

Section 2

Summary of Accomplishments

A summary of the most important contributions of the present and previous programs, in part supported by other related contracts, follow:

1. Experiments were performed which demonstrated that lasers with several joules of pumping energy could be used to generate sufficient x-rays to pump laboratory scale short wavelength lasers.
2. Following earlier work of Mcguire, the concept of Auger lasers was proposed and developed.
3. We invented and demonstrated a novel traveling wave geometry which has been key to much of the success of this program. This geometry allows a long interaction length with adjustable group velocity matching of the pumping x-rays and the generated XUV laser beam.
4. Using this geometry, the fully saturated operation of a Xe Auger laser (earlier demonstrated by Roger Falcone) was shown.
5. The concept of pumping by x-ray produced electrons was suggested and demonstrated in Li.
6. The combination of the traveling wave geometry and the electron pumping was used to make the first laser where the upper level is above a lower continuum. This laser operated at 96.9 nm and had a demonstrated small signal gain in excess of exp(80). [*Phys. Rev. Lett.* **61**, 2201–2204 (November 1988)].

7. An improved version of the traveling wave geometry was used to demonstrate lasing in molecular hydrogen at 116 nm.

8. Operation of the Xe Auger laser (108.9 nm) was demonstrated at 2 Hz.

9. A method to use an applied electromagnetic field to construct a laser which operates without the requirement of population inversion was suggested. [*Opt. Lett.* **14**, 1344–1346 (December 1989)].

10. The possibility of greatly improved nonlinear optical processes, which operate by causing transparency in otherwise opaque media was noted. [*Phys. Rev. Lett.* **64**, 1107–1110 (March 1990)].

11. In very recent work we have shown the ability to change the opacity of a material by a factor of exp(14).

Section 3

Publications Supported

1. A. Imamoğlu and S. E. Harris, "Lasers Without Inversion: Interference of Dressed Lifetime Broadened States," *Opt. Lett.* **40**, 1344–1346 (December 1989).
2. M. H. Sher, S. J. Benerofe, J. F. Young, and S. E. Harris, "A 2 Hz 109 nm Mirrorless Laser" (to be published).
3. S. E. Harris, J. E. Field, and A. Imamoğlu, "Nonlinear Optical Processes Using Electromagnetically Induced Transparency," *Phys. Rev. Lett.* **64**, 1107–1110 (March 1990).
4. K. H. Hahn, D. A. King, and S. E. Harris, "Nonlinear Generation of 104.8 nm Radiation Within an Absorption Window in Zinc" (to be published)
5. A. Imamoğlu, J. E. Field, and S. E. Harris, "Lasers Without Inversion: A Closed Lifetime Broadened System" (submitted for publication).

Section 4

Appendixes

Lasers without inversion: interference of dressed lifetime-broadened states

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Received July 25, 1989; accepted October 4, 1989

We describe the use of a coupling electromagnetic field to provide a general method of producing inversion-free laser systems. The interference between dressed states produces a zero in absorption while allowing gains of the order of that of the uncoupled system.

It has recently been shown that if two upper states of a three-state laser system (Fig. 1) are purely lifetime broadened and decay to an identical continuum, this decay couples these states and results in nonreciprocal emission and absorption profiles.[1,2] One may obtain a zero in the absorption cross section and, for states that are spaced by several inverse lifetimes, obtain nearly the full gain cross section of a single transition.

The problem is that it is not easy to find nearby states that decay strictly to the same continuum. For states that decay by autoionization and Auger processes there are almost always several channels into which the state may decay. For states that decay by radiation, the decay rate is determined by interaction with the vacuum fluctuations, while their spacing is determined by electrostatic interactions; such states are therefore most often spaced by many inverse lifetimes.

In this Letter we show how to use an additional electromagnetic field to create a pair of interfering dressed states that *a priori* decay to the same continuum. Figure 2(a) shows the bare states and the electromagnetic field that is applied; Fig. 2(b) shows the equivalent dressed-state system. In the following we show that the effect of the interference of these dressed states is to create a zero in the absorption profile of state $|1\rangle$ atoms. In all cases this zero occurs at an energy that is the sum of the energies of (bare) state $|2\rangle$ and the coupling electromagnetic field. The emission profile of excited state $|2\rangle$ atoms does not exhibit this zero and, in fact, may have a gain cross section at the frequency of the zero that is of order of the gain cross section of the bare $|3\rangle$–$|1\rangle$ transition. This method thereby permits a general class of lifetime-broadened lasers that may operate without inversion.

In Fig. 2(a) we view the strength Ω_{23} and frequency ω_c of the coupling electromagnetic field as fixed and consider the gain and loss as a function of the probe frequency ω_p. We take the probe intensity Ω_{13} to be small as compared with Ω_{23} and Γ_3, where Γ_3 is the decay rate (to an arbitrary continuum) of state $|3\rangle$. The frequency detunings of the bare system are defined as $\Delta\omega_c = \omega_3 - \omega_2 - \omega_c$ and $\Delta\omega_p = \omega_3 - \omega_p - \omega_1$.

We transform to the equivalent dressed-state[3] system of Fig. 2(b). We assume that only a single pair of dressed states is in the vicinity of the probe frequency and that all other pairs may be neglected. The transformation from bare states $|2\rangle$ and $|3\rangle$ to dressed states $|2d\rangle$ and $|3d\rangle$ is

$$|2d\rangle = \cos\theta|2\rangle - \sin\theta|3\rangle,$$
$$|3d\rangle = \sin\theta|2\rangle + \cos\theta|3\rangle,$$
$$\tan 2\theta = \frac{-\Omega_{23}}{\Delta\omega_c}. \tag{1a}$$

The equivalent decay rates, Rabi frequencies, and detunings of the dressed system of Fig. 2(b) are then

$$\Gamma_{2d} = \Gamma_3 \sin^2\theta, \qquad \Gamma_{3d} = \Gamma_3 \cos^2\theta,$$
$$\Omega_{12d} = -\Omega_{13}\sin\theta, \qquad \Omega_{13d} = \Omega_{13}\cos\theta,$$
$$\Delta\omega_{2d} = \omega_2 - \frac{\delta}{2} + \omega_c - \omega_1 - \omega_p,$$
$$\Delta\omega_{3d} = \omega_3 + \frac{\delta}{2} - \omega_1 - \omega_p,$$
$$\delta = \frac{\Delta\omega_c(1 - \cos 2\theta)}{\cos 2\theta}. \tag{1b}$$

To obtain the absorption profile of the probe beam,

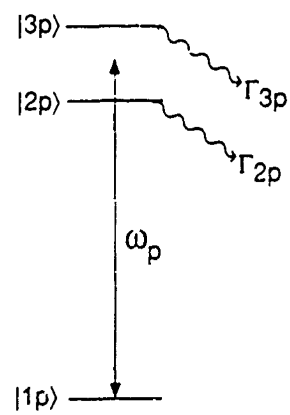

Fig. 1. Prototype system for inversion-free lasers. Γ_{2p} and Γ_{3p} are the decay rates, to the same continuum, of prototype states $|2p\rangle$ and $|3p\rangle$.

0146-9592/89/241344-03$2.00/0

A 2 Hz 109 nm Mirrorless Laser*

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Abstract

We report 2 Hz operation of a single-pass 109 nm laser with a small signal gain of exp(33) and a saturated output energy of 1 μJ. The laser is based on an oblique-incidence, laser-produced-plasma pumping geometry and requires only 500 mJ of 1064 nm energy in a 0.5 nsec pump pulse. We have used the laser to produce a two slit interference pattern and have demonstrated a focusable intensity of greater than 10^9 Wcm^{-2}.

* This work was jointly supported by the U.S Office of Naval Research, the U.S. Air Force Office of Scientific Research, the U.S. Army Research Office, and the Strategic Defense Initiative Organiation.

Nonlinear Optical Processes Using Electromagnetically Induced Transparency

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(Received 27 December 1989)

We show that by applying a strong-coupling field between a metastable state and the upper state of an allowed transition to ground one may obtain a resonantly enhanced third-order susceptibility while at the same time inducing transparency of the media. An improvement in conversion efficiency and parametric gain, as compared to weak-coupling field behavior, of many orders of magnitude is predicted.

PACS numbers: 42.65.Ky, 42.50.Hz, 42.50.Qz

It is well known by those practicing the techniques of nonlinear optics that the power which may be generated in a frequency summing process, or the gain which may be obtained in a parametric process is determined by the interplay of the nonlinear and linear susceptibilities.[1,2] In general, as an atomic transition to the ground state is approached, the nonlinear susceptibility is resonantly enhanced, but at the same time the media exhibits a rapidly increasing refractive index and becomes opaque.

In this Letter we show how it is possible to create nonlinear media with resonantly enhanced nonlinear susceptibilities and at the same time induce transparency and a zero in the contribution of the resonance transition to the refractive index. An energy-level diagram for a prototype system is shown in Fig. 1. We apply a strong electromagnetic coupling field of frequency ω_c between a metastable state $|2\rangle$ and a lifetime-broadened state $|3\rangle$, and generate the sum frequency $\omega_d = \omega_a + \omega_b + \omega_c$. We assume that $|1\rangle$-$|3\rangle$ is a resonance transition and that in the absence of ω_c, radiation at ω_d is strongly absorbed.

When the Rabi frequency of the coupling field exceeds the Doppler width of the $|1\rangle$-$|3\rangle$ transition, the media becomes transparent on line center. This transparency occurs because of the destructive interference of the split (Autler-Townes) components of the $|1\rangle$-$|3\rangle$ transition. Though one might expect that this interference would also negate the nonlinearity that causes the generation of ω_d, this is not so; because of a sign change in the dressed eigenvectors, for generated frequencies lying between the Autler-Townes components, there is a constructive rather than a destructive interference in the nonlinear susceptibility.

Before proceeding we note earlier work: The use of electromagnetic fields to create transparency has been reviewed by Knight.[3] Armstrong and Wynne[4] observed that Fano-type interferences between photoionization and autoionization are not mirrored in $\chi^{(3)}$ profiles; Pavlov *et al.*[5] observed an enhancement of sum frequency generation by inducing a Fano-type state into the continuum. The work described here does not involve photoionization. State $|3\rangle$ may decay radiatively, or by autoionization, but if it decays by autoionization, then this work neglects the direct coupling of states $|1\rangle$ and $|2\rangle$ to the continuum.

In the following paragraphs we first consider the dressed susceptibilities of a single atom and thereafter include the effects of collisional and Doppler broadening.

We assume that an electromagnetic field with the frequencies ω_a, ω_b, ω_c, and ω_d is applied to the atom and calculate the total dipole moment at ω_d. This dipole moment may be expressed in terms of a linear and a third-order susceptibility. These susceptibilities depend on the magnitude of the coupling field ω_c and in this sense are dressed by the field. The pertinent quantities are defined as

$$E(t) = \mathrm{Re}\left\{\sum_{k=a}^{d} E(\omega_k)e^{j\omega_k t}\right\}, \quad P(t) = \mathrm{Re}\left\{\sum_{k=a}^{d} P(\omega_k)e^{j\omega_k t}\right\},$$
$$P(\omega_d) = \epsilon_0\chi_D^{(1)}(-\omega_d,\omega_d)E(\omega_d) + \tfrac{3}{2}\epsilon_0\chi_D^{(3)}(-\omega_d,\omega_a,\omega_b,\omega_c)E(\omega_a)E(\omega_b)E(\omega_c). \tag{1}$$

The susceptibilities are calculated from the equations for the time-varying probability amplitudes of a single atom

$$\frac{db_1}{dt} = \frac{j\Omega_{12}}{2}b_2 + \frac{j\Omega_{13}}{2}b_3, \quad \frac{db_2}{dt} + j\Delta\tilde{\omega}_{21}b_2 = \frac{j\Omega_{12}^*}{2}b_1 + \frac{j\Omega_{23}}{2}b_3, \quad \frac{db_3}{dt} + j\Delta\tilde{\omega}_{31}b_3 = \frac{j\Omega_{13}^*}{2}b_1 + \frac{j\Omega_{23}^*}{2}b_2, \tag{2a}$$

$$\Delta\tilde{\omega}_{21} = \Delta\omega_{21} - \frac{j\Gamma_2}{2}, \quad \Delta\tilde{\omega}_{31} = \Delta\omega_{31} - \frac{j\Gamma_3}{2}, \quad \Omega_{12} = \sum_i \frac{\Omega_{1i}\Omega_{i2}}{2}\left(\frac{1}{\omega_i - \omega_a} + \frac{1}{\omega_i - \omega_b}\right). \tag{2b}$$

The Ω_{ij} are the respective Rabi frequencies; Ω_{12} is an effective Rabi frequency which is obtained by summing over in-

Nonlinear Generation of 104.8 nm Radiation Within an Absorption Window in Zinc

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Abstract

Two autoionizing levels which are separated by a few decay widths may exhibit a sharp interference or window in their absorption profile and also make cancelling contributions to the refractive index at the absorption minimum. A correct choice of intermediate mixing levels prevents a similar cancellation in the nonlinear susceptibility. Using UV lasers with energies of about a mJ and pulse lengths of 5 ns, we generate 0.23 μJ per pulse at 104.8 nm.

Lasers Without Inversion:

A Closed Lifetime Broadened System

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Abstract

We show a model laser system which operates by an electromagnetically induced interference. The system, in principle, lases without inversion in steady state and is pumped by incoherent radiation on the transition on which lasing occurs.